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A STUDY OF CORRUGATED FIBERBOARD

THE EFFECT OF ADHESIVE ON THE STRENGTH OF CORRUGATED BOARD

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A STUDY OF CORRUGATED FIBERBOARD

THE EFFECT OF ADHESIVE ON THE STRENGTH OF CORRUGATED BOARD

The use of corrugated fiberboard boxes has approximately doubled during the past decade. Practically every article of commerce is packaged with corrugated board. This universal acceptance has been achieved because corrugated fiberboard provides strong, resilient, and light-weight packaging at low cost.

The primary requisite of a shipping container is to provide adequate protection for its contents. A corrugated fiberboard box must be sufficiently strong so as to prevent damage to its contents by any anticipated force to which the box is likely to be subjected. The specific-strength requirement of a box will depend upon the nature of its contents and upon the transportation and storage conditions to which it will be exposed. It is desirable that the required strength be obtained at the lowest possible cost. For these reasons increasing consideration is being given to the strength of corrugated boxes.

The strength of a corrugated fiberboard box depends upon the strength of the board from which it is constructed, the design of the box, and fabricating practices. When fabricating practices are good, box strength depends upon fiberboard strength.

The strength of corrugated fiberboard has generally been recognized to be dependent upon the strengths of the boards used for liners and corrugating medium, and upon the corrugating machine adjustments and operating conditions. The influence of the adhesive on the strength of the corrugated board has not been fully appreciated.

The research reported in this bulletin was initiated to study the contribution of the adhesive to the strength of corrugated fiberboards and boxes. It is hoped that the present and future results of this research may evaluate this contribution in a way such that proper selection and application of adhesives will result in stronger containers.

SUMMARY

Six lots of corrugated fiberboard were received which had been fabricated from uniform materials under conditions such that mechanical defects in the boards were minimized. Carefully fabricated boxes had been made from each of the boards in a manner described in this bulletin. The only differences in the fiberboards and boxes were in the types and amounts of adhesives used. Descriptions of the boards are:

Adhesive Used	*Amount of Adhesive*
Silicate	Normal application
Silicate-Clay	Normal application
Starch	Normal application
Silicate	Heavy application
Silicate-Clay	Heavy application
Starch	Heavy application

The boards were evaluated by seven test procedures under controlled conditions of temperature and humidity. The compression strengths of the boxes were evaluated by a recognized commercial laboratory.

A summary of the pertinent test data is given in Table I.

The data in Table I reveal that:

1. The Mullen test of fiberboard does not evaluate the board in a way comparable to the compression strength of boxes made from the board. The reverse is indicated in these data, in that the boards having the greatest Mullen test values produced the weakest boxes.

2. The structural tests on the fiberboard, that is, evaluations by column and beam loading, vary in test values in a manner similar to the compression strength tests of the boxes. The values obtained with these tests on fiberboards are indicative of the compression strengths of the boxes made from the boards.

TABLE I

Properties of Corrugated Fiberboards and Boxes

Board	Mullen Test Lbs./in.^{2}	*Compression Strength of Boxes, Lb.		Structural Tests on Paperboard		
				Column Load Lbs.	Beam Loading	
		Top to Bottom	End to End		Breaking Load Lbs.	Deflection at Constant Load, 2.8 Lbs./in.
Silicate—Normal	226.8	1021	765	171	4.9	0.431
Silicate-Clay—Normal	232.6	1082	777	194	5.2	0.413
Starch—Normal	243.6	916	729	153	4.5	0.546
Silicate—Heavy	210.2	1229	794	209	5.7	0.387
Silicate-Clay—Heavy	219.2	1074	787	222	6.0	0.345
Starch—Heavy	244.7	899	677	161	4.3	0.586

Tests on paperboard at 70°F. and 50% Relative Humidity.
Mullen tests—single face up.
Column tests—4"×4" samples; corrugations vertical.
Beam tests—center loading, 3"×12" beam, corrugations parallel to beam length, single face up.

* *Box Compression Strength Data from D. L. Quinn Company, Chicago, Illinois.*

3. The four boards made with silicate adhesives and the boxes made from these boards were, structurally, considerably stronger than the similar boards and boxes made with the starch adhesive.

4. The use of heavy applications of silicate adhesives increased considerably the structural strength of the fiberboards. No equal benefits resulted from the use of heavy applications of the starch adhesive.

The structural data obtained on the corrugated boards have been theoretically correlated with the structural properties of boxes. The modulus of elasticity of fiberboard, which is an expression of its stiffness, has been used to predict the compression strength of boxes, with sufficient success so that the modulus may be considered to be indicative of box strength.

EXPERIMENTAL PROCEDURE

In order to evaluate the contribution of the adhesive to the strength of corrugated board, it is necessary to fabricate boards and boxes as free from mechanical defects as possible. The influences of finger marks and score lines on strength properties are fully realized. Thus, sample lots of boards and boxes were made under very close and expert supervision so as to eliminate as far as possible all factors except those that could be considered to be attributable to the adhesive used.

Tests on the boards were performed under controlled conditions of temperature and humidity, and they were made after the test pieces had been adequately exposed to test conditions. The test pieces used were selected so as to minimize the influences of finger marks and other visible mechanical defects, as the purposes of tests were to evaluate the contributions of the adhesive to the corrugated board.

Fabrication of Boards and Boxes:

Six lots of corrugated fiberboard, "A" flute, were made on a pressure type corrugating machine which was in good condition. All boards were made with the similar machine adjustments, during a single day and by the same operators. The machine operated at a rather slow speed of 110–115 feet per minute, so as to assure the production of uniform board. The three paperboards used to make the corrugated fiberboards were from three reels which were sampled at the beginning and end of the run. The uniformity of the paper boards used is indicated by the test data on these samples, which are given in Table II.

Corrugated fiberboards were made with normal and heavy applications of adhesives.

The corrugating machine was used for normal applications of adhesive

TABLE II

*Properties of Paperboards Used in Fabrication of Corrugated Boards**

Papers	Basis Wgt. Lbs.	Tensile Strength		Mullen Strength		Crush Strength	
		With Grain Lbs.	Cross Grain Lbs.	Felt Side Up Lbs.	Wire Side Up Lbs.	With Grain Lbs.	Cross Grain Lbs.
Single-Face Liner	42–44						
16 pt. Kraft							
Start		50.55	25.55	113.4	106.7	74.2	55.0
End		50.15	23.10	115.4	99.8	70.4	56.3
Double-Face Liner	42–44						
16 pt. Kraft							
Start		48.10	22.35	109.1	100.3	66.5	53.8
End		51.60	25.40	110.8	101.5	71.6	58.9
Corrugating Medium	26						
9 pt. Kraft							
Start		39.9	15.20	83.2	70.1	32.0	19.2
End		37.5	14.90	88.5	84.5	37.1	21.7

* Averages of 10 tests at 50% Relative Humidity.

at the setting regularly used for the application of starch adhesive, the adhesive normally used on this machine. Heavy applications of adhesive were obtained by increasing the clearance on the transfer rolls. The starch adhesive was from a normal commercial batch and was representative of types of these adhesives which are used in board manufacture. The silicate adhesives were: sodium silicate with a silica-soda ratio of 3.25 and gravity of 41.5° Be. at 60°F.; and a silicate-clay adhesive which was representative of commercial grades.

The six lots of board that were made and their descriptions are given in Table III.

Boxes, size $13\frac{3}{4}'' \times 10\text{-}5/16'' \times 9\frac{1}{2}''$ inside dimension, were fabricated

TABLE III

Description of Corrugated Fiberboards

Designation	Adhesive Used	Application	Estimated Amount of Adhesive—Lbs. per 1000 sq. ft.
Si–N	Silicate	Normal	21–22
Si–C–N	Silicate-Clay	Normal	22–24
Sh–N	Starch	Normal	16
Si–H	Silicate	Heavy	30–32
Si–C–H	Silicate-Clay	Heavy	32–34
Sh–H	Starch	Heavy	24–26

from the six lots of boards. They were fabricated on the same machine with identical settings for scoring, slotting, and taping.

By the above means and also by the close supervision of fabrication by representatives of the Sodium Silicate Manufacturers Institute, it was considered that both the boards and boxes were made under nearly identical mechanical conditions, and that operating practices were exceptionally good. Thus, the materials supplied would differ only in the types and amounts of adhesives used, and could be used to evaluate the contribution of the adhesive to the strength of corrugated boards and boxes.

Evaluation of Boxes:

Boxes made from the six lots of board were submitted to the Don L. Quinn Co. laboratories for evaluation by the box compression test. These tests were made after conditioning the boxes to the standard moisture content of 7.2%.

Evaluation of Corrugated Fiberboards:

Adequate samples of the six lots of boards were received for evaluation. The boards were stored under normal atmospheric conditions. All testing was done in a controlled temperature and humidity room, and all test pieces of board were conditioned in the room for at least twenty-four hours before testing. Care was exercised to minimize the influences of finger marks and other mechanical defects on the test pieces. Seven test procedures were used on each lot of board.

Transverse Beam Test: The transverse beam test was used to evaluate the structural properties of fiberboard when subjected to bending loads. The apparatus used, designed similar to the one reported by Heritage, Schafter, and Carpenter,* is shown in Figure 1.

A sample of board is supported at its ends on two rods, and the load is applied to the top of the sample by a saddle at a point equidistant between the end supports. The method of loading consists of hanging a bucket on the loading saddle and adding water to the bucket at a steady and measured rate. The load at a given time is the initial load of the bucket plus the weight of water added. Deflection of the center of the beam from the initial horizontal position is measured during a test by direct observation of a pointer which is attached to the loading saddle and turns as the saddle depresses the beam. Tests are continued until the beam ruptures. The deflection at rupture is observed directly and the

* Heritage, Schafter, and Carpenter, Paper Trade Jour., #17, p. 50 (Oct., 1924).

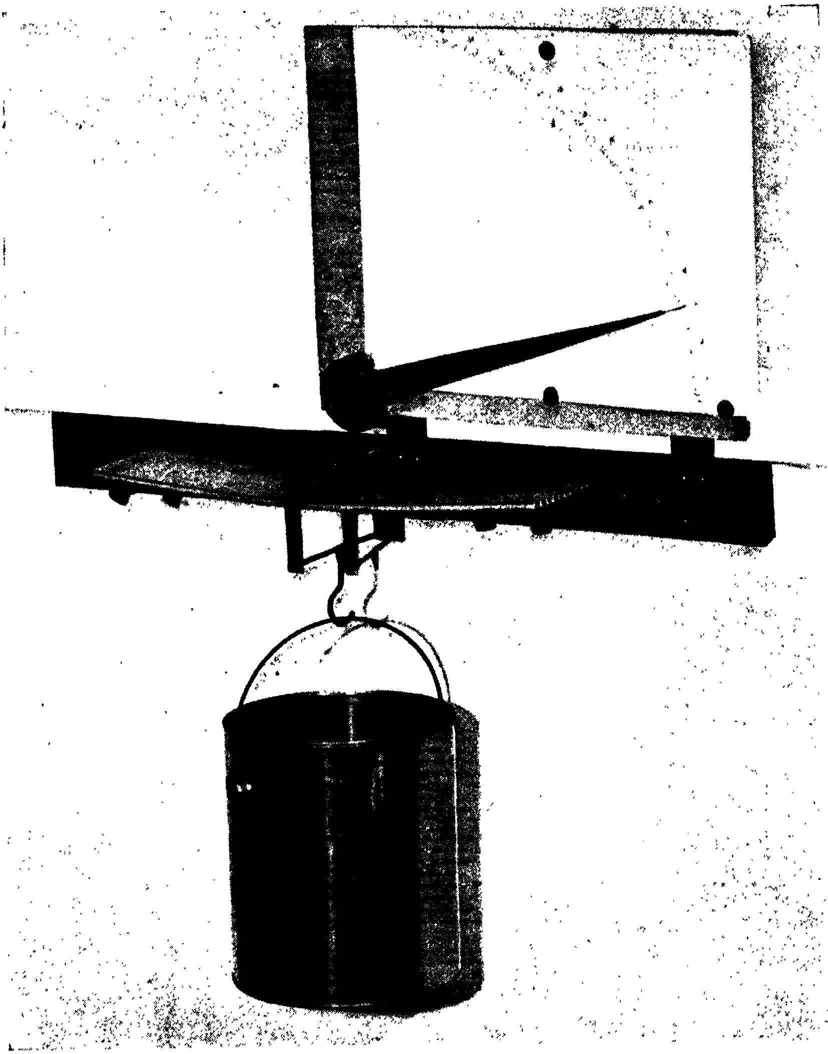

Figure 1. Transverse Beam Tester.

rupture load measured as the weight of the bucket. Typical load-deflection data are plotted in Figures 8–12.

Test pieces of board were cut two inches longer than the distance between the supports for the beam. Tests were made on samples with corrugations both parallel and perpendicular to the length of the beam.

The values obtained in the beam test depend upon the dimensions of the beam tested, and beams of several sizes were tested in order to establish a standard procedure. The results of tests on beams of various sizes are given in Table IV.

A test piece size 3″×14″, which gives a beam size of 3″×12″, was chosen as the standard size as it gave measurable loads and deflections within the best ranges for the instrument. All reported beam tests are for this size of sample.

Failures of beams, when the corrugations are perpendicular to the length of beam, occur when the top liner fails due to compression. This usually occurs between two glue lines and the liner folds between two flutes. Failures of beams, when the corrugations are parallel to the length of beam, are due to crushing, by compression, of the top side of the beam. Both the top liner and the tops of the flutes are crushed. These two types of failures are shown in Figure 2.

TABLE IV

Beam Tests on Various Sizes of Samples

Size of Test Piece, Inches	Board; Silicate Adhesive, Normal Application, Corrugations Parallel to Beam Length		
	Length of Beam, Inches	Load at Rupture, Grams	Deflection at Rupture, Inches
2″× 8″	6	2296	0.21
3″× 8″	6	3231	0.20
2″×10″	8	2128	0.33
2″×14″	12	1476	0.79
3″×14″	12	2457	0.79
2″×20″	18	1155	1.25

The beam test is rather precise and the variation in values obtained are well within the extremes usually allowable in testing paper products.

Column Compression Test: The column compression test was used to measure the structural resistance of corrugated boards when loaded as columns. The apparatus used was patterned similar to one reported by Drewson* and is shown in Figure 3.

Samples of board are placed between the platens of the tester. The load is applied by means of an hydraulic jack beneath the lower platen. The hydraulic jack is actuated by oil which is forced from an oil reservoir by high pressure (400 lbs./sq. in.) nitrogen. The upper platen is fixed on a steel beam which deflects as the load is applied. This steel beam is

* Drewson, Tech. Assoc. Papers, 21, p. 162 (June, 1938).

calibrated so that its deflection, as measured by a micrometer gauge, indicates the load on the sample.

Test pieces 4″×4″ were used in the column test and these were tested with corrugations both vertical and horizontal. Clamps were placed on

Figure 2. Types of Failures—Transverse Beam Test.

the ends of the columns next to the platens to prevent slipping and buckling of the ends. A sample being tested as a column is shown in Figure 4.

Failures of columns tested with corrugations horizontal are always due to buckling, somewhere in the column, with a liner folding between two flutes. Failures of columns tested with corrugations vertical are usually

due to buckling in the middle of the column, but the buckling may or may not be preceded by telescoping of the ends of the column These two types of failures are shown in Figure 5

The individual test values obtained with the column test are surprisingly consistent considering the opportunities for deviation The precision of the test is compatible with the precision of the usual paper testing methods

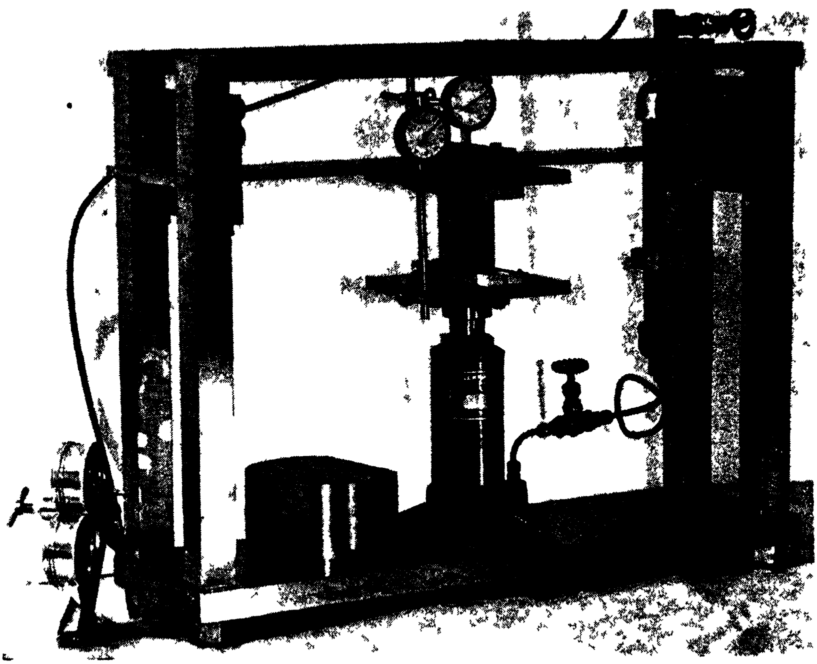

Figure 3 Column Compression Tester

Flat Compression Test The flat compression test was used to evaluate the resistance of fiberboard to crushing of the corrugations The same apparatus was used as was used for the column tests The distance between the platens was decreased by placing a block under the jack. A sample in flat compression test is shown in Figure 6.

Test pieces are cut 4″×4″ and placed between the platens and the pressure applied Compression of the board is measured by the decrease in the distance between the platens, and the compressing load by the deflection of the steel beam.

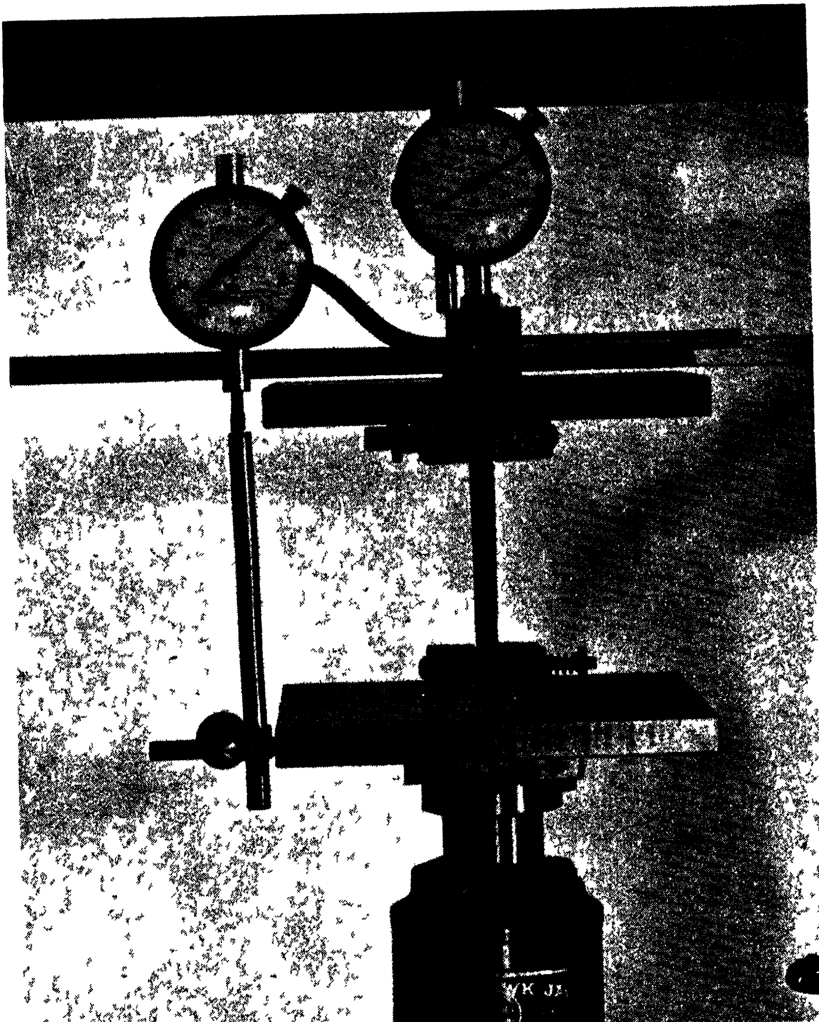

Figure 4 Column Compression Test Sample

Failure of a board occurs by two steps: the first, when the resistance of the corrugating medium to compression is overcome and the board begins to collapse, and second, after the corrugated medium has been greatly deformed and can no longer resist compression, so that the board collapses completely Often the two collapses occur simultaneously At the first collapse the board usually compresses to such an extent that the

load on the board is decreased for an instant, until the jack can travel far enough to again apply load Usually, if the load applied by the jack is held at the value of the first collapse, the board will gradually collapse completely.

Figure 5 Types of Failures—Column Compression Test

The loads causing the initial collapse are uniformly consistent. The loads causing ultimate collapse vary considerably and the variations are larger than the usual tolerances allowed in paper testing.

Mullen Test: The Mullen strength test was made on a hand-operated Jumbo Mullen Tester according to the recommended practice.

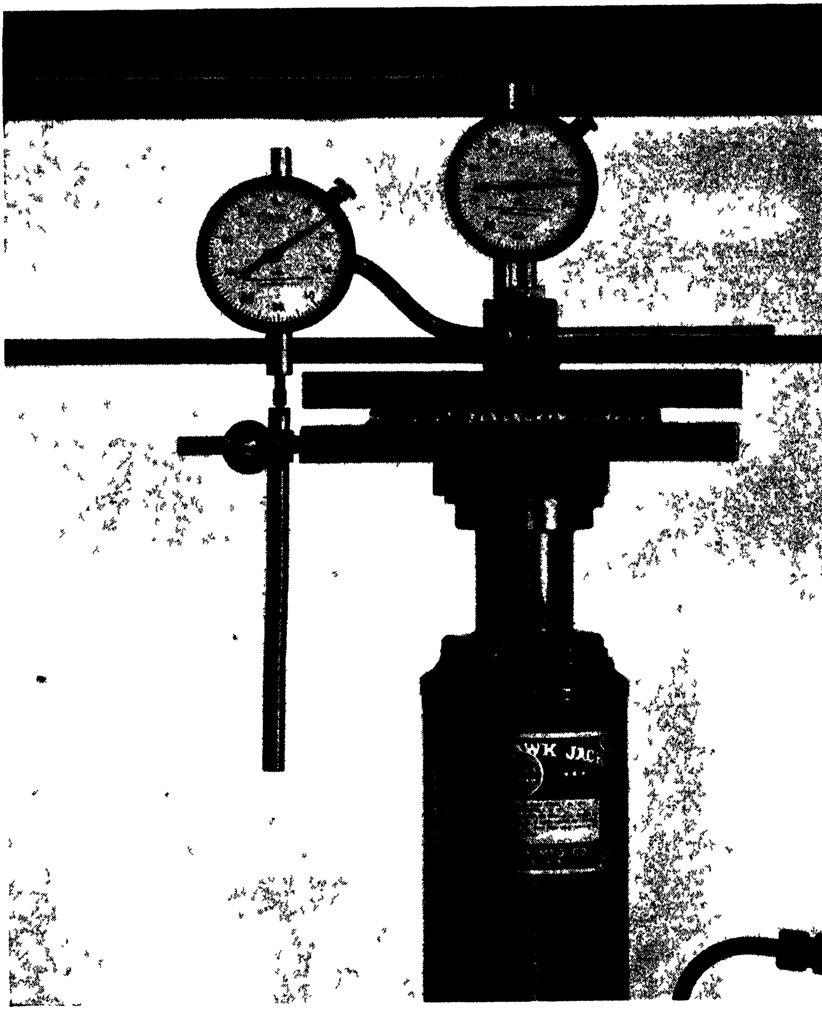

Figure 6 Flat Compression Test Sample

Bond Strength Test. The bond strength test was used to measure the adhesion of the corrugating medium to the liners

A sample of board 1$\frac{3}{8}$″ wide is used and into this board are inserted 9 rods in successive flutes so that five are pressing against the corrugating medium and four against a liner A fixture is used so that successive rods are pushed in opposite directions The assembled fixture is placed in the compression tester and the force required to separate the liner from the

corrugating medium measured. Rupture is usually instantaneous. The test values on a single board varied greatly and this test is not considered reliable.

Paperboard Compression Test: This test was used to measure the crushing resistance of the paperboards from which the corrugated fiberboards were made. Both samples of unused liner boards and liner boards from which the corrugating mediums were removed were tested.

Samples of paper, 6″ × ½″, are held as cylindrical columns in a 1.875″ diameter template and loaded in the compression tester until rupture occurs. Individual tests are within the usual limits allowable in paper testing procedures.

EXPERIMENTAL RESULTS AND DISCUSSION

A large amount of experimental data was obtained. The data are presented rather completely and the results of each test are discussed. A correlation of the pertinent data with box strength is presented in the summary of this report. A theoretical discussion and application of the data are presented in the theoretical part.

Compression Strength of Boxes:

The results of the tests on the compression strengths of the boxes made from the six lots of test board are given in Table V. In the group where normal amounts of adhesives were used in making the boards, boxes made from silicate boards tested about the same and were 10–15 per cent stronger than boxes made from the starch board. The use of heavy applications of adhesive increased considerably the strength of boxes made from the straight silicate board, caused little change in the strength of boxes made from the silicate-clay board, and decreased slightly the strength of boxes made from the starch board.

TABLE V
*Compression Strength of Boxes**

Board		Maximum Loads, Pounds	
Adhesive	Application	Top to Bottom	End to End
Silicate	Normal	1021	765
Silicate-Clay	Normal	1082	777
Starch	Normal	916	729
Silicate	Heavy	1229	794
Silicate-Clay	Heavy	1074	787
Starch	Heavy	899	677

* Averages of 20 tests at 7.2 per cent moisture content.

The above results indicate that boxes made from corrugated board glued with silicate adhesives resist greater compressing loads than boxes made from starch pasted board; also, that the use of heavier applications of silicate adhesive increases box strength. Apparently, this does not occur when heavy applications of starch adhesive are used.

Transverse Beam Tests: The transverse beam test data are summarized in Table VI and plotted in detail in Figures 8–12. These data are rather completely presented for it is considered that the data from the beam or bending test indicate some of the fundamental strength characteristics of corrugated fiberboard. The bending of corrugated board to the point where its structure collapses often is the cause of failure of containers.

This resistance of the board to bending, or its stiffness, is an essential strength characteristic. The failure of corrugated board when bent usually occurs after a certain degree of bending has been caused. This is indicated in the data on deflection at rupture in Table VI. The values of deflection vary from 0.27 to 0.31 inch when the corrugations are perpendicular to the length of the beam and from 0.72 to 1.07 when the corrugations are parallel to the length of the beam. However, most of the values are closer to mean values of 0.29 and 0.80 inch. Thus, it may be considered that failure of corrugated board occurs when the extent of bending has reached a critical value for the structure, as the structure allows only a certain amount of displacement before it collapses.

The important consideration from the beam test is the resistance offered by the corrugated fiberboard to bending or its stiffness. Thus, stronger boards are those that require greater loads to bend them to the critical extent allowed by the structure. Comparison of rupture load values, at the same testing conditions of relative humidity, shows that greater loads were required to rupture the silicate boards than the starch boards with one exception; that being with normal application of adhesive and testing conditions of 85% relative humidity. In most instances, the boards glued with silicate-clay adhesive required greater loads for rupture than those glued with silicate adhesive.

The data at rupture are important as they give the ultimate strength of the board. However, it is often desirable to consider the strength properties of the board at loads which are less than the breaking loads. For this reason, two other values are given: the deflection of the beam of fiberboard at 2 lbs. load; and the load the beam withstood at a deflection of ½ inch when the corrugations were parallel to length of the beam, and at a deflection of ¼ inch when the corrugations were perpendicular.

Comparisons of the above values in Table VI show that there were

TABLE VI

Results of Transverse Beam Tests
3″×12″ Beams

	Relative Humidity	Si-N	Si-C-N	Sh-N	Si-H	Si-C-H	Sh-H
Rupture Load, lbs.; corrugations parallel to beam							
Single Face Up	50	4.93	4.22	4.53	5.67	5.97	4.29
	70	4.23	3.88	3.62	4.16	4.23	3.84
	85	3.29	3.25	3.29	3.69	3.90	3.32
Double Face Up	50	5.49	5.90	4.19	5.82	6.67	4.58
Rupture Load, lbs.; corrugations perpendicular to beam							
Single Face Up	50	3.03	2.93	2.60	3.30	3.21	2.54
Double Face Up	50	3.24	3.47	2.65	3.54	3.58	2.76
Deflection at Rupture, inches, corrugations parallel to beam							
Single Face Up	50	0.72	0.77	0.84	0.83	0.83	0.78
	70	0.83	0.77	0.77	0.86	0.85	0.83
	85	0.83	0.77	0.89	0.87	1.01	0.90
Double Face Up	50	0.80	0.84	0.72	0.99	1.07	0.88
Deflection at Rupture, inches, corrugations perpendicular to beam							
Single Face Up	50	0.29	0.27	0.29	0.32	0.30	0.28
Double Face Up	50	0.29	0.30	0.27	0.31	0.31	0.29
Deflection at 2 lbs. load, inches, corrugations parallel to beam							
Single Face Up	50	0.217	0.200	0.268	0.200	0.179	0.277
	70	0.271	0.273	0.309	0.282	0.271	0.313
	85	0.339	0.341	0.373	0.320	0.313	0.371
Double Face Up	50	0.206	0.198	0.253	0.214	0.193	0.262
Deflection at 2 lbs. load, inches, corrugations perpendicular to beam							
Single Face Up	50	0.162	0.162	0.217	0.166	0.158	0.194
Double Face Up	50	0.205	0.198	0.230	0.170	0.159	0.223
Load at ½″ deflection, lbs.; corrugations parallel to beam							
Single Face Up	50	3.98	4.10	3.33	4.40	4.74	3.26
	70	3.25	3.20	2.90	3.13	3.22	2.87
	85	2.61	2.62	2.47	2.73	2.78	2.49
Double Face Up	50	4.25	4.33	3.47	4.04	4.41	3.38
Load at ¼″ deflection, lbs.; corrugations perpendicular to beam							
Single Face Up	50	2.70	2.76	2.20	2.83	3.09	2.29
Double Face Up	50	2.56	2.66	2.26	2.54	2.63	2.16

usually slight differences in the test values obtained with the two silicate boards. The silicate boards were always considerably stiffer than the starch boards at the humidities used. Thus, at the same load, starch pasted boards bend considerably more, 10 to 30%. And, if a deflection of ½ inch is allowable, silicate boards will sustain greater loads, 8 to 40% before this deflection is reached.

The results of the beam tests are precise and the data obtained from them are used in the theoretical part of this report to predict box strength.

TABLE VII

Column Compression Tests

Relative Humidity	Silicate Normal	Silicate-Clay Normal	Starch Normal	Silicate Heavy	Silicate Clay Heavy	Starch Heavy
		Rupture load, lbs., corrugations vertical				
(1) 50	172	194	153	209	222	161
(1) 70	133	130.5	120	140	151	138
(2) 85	101	110	106	113	129	115
		Rupture load, lbs., corrugations horizontal				
(1) 50	73	88.3	73	71.7	84.5	69

(1) Average of 10 tests.
(2) Average of 5 tests.

Column Compression Tests: The results of the column compression tests are reported in Table VII. The data show that the fiberboards made with silicate-clay adhesive withstood greater loads. At the normal humidity of 50 per cent, silicate boards have considerably greater strength than starch boards when loaded as columns. The use of heavier applications of adhesive increased the strength of the boards.

At the higher relative humidities all the boards test closer to the same values. This trend is noticeable in many of the tests made on the boards, and it might readily be attributed to weakening of the paper fibers at the higher humidities.

Flat Compression Tests: The results of the flat compression tests are reported in Table VIII. Two test values are reported for both crushing loads and extent of compression. They are the values for initial failure of the boards, and for the ultimate collapse of the boards. In Figure 7 are plotted the data on load versus compression of the boards.

The values for initial failures of the boards are the readings at the

TABLE VIII

*Flat Compression Tests**

Board		Crushing Load		Compression	
Adhesive	Application	Initial Lbs.	Ultimate Lbs.	Initial Inches	Ultimate Inches
Silicate	Normal	210	265	0.024	0.084
Silicate-Clay	Normal	210	260	0.024	0.072
Starch	Normal	220	275	0.024	0.082
Silicate	Heavy	270	285	0.029	0.040
Silicate-Clay	Heavy	275	285	0.032	0.040
Starch	Heavy	255	315	0.025	0.060

* Average of 10 tests at 50% Relative Humidity.

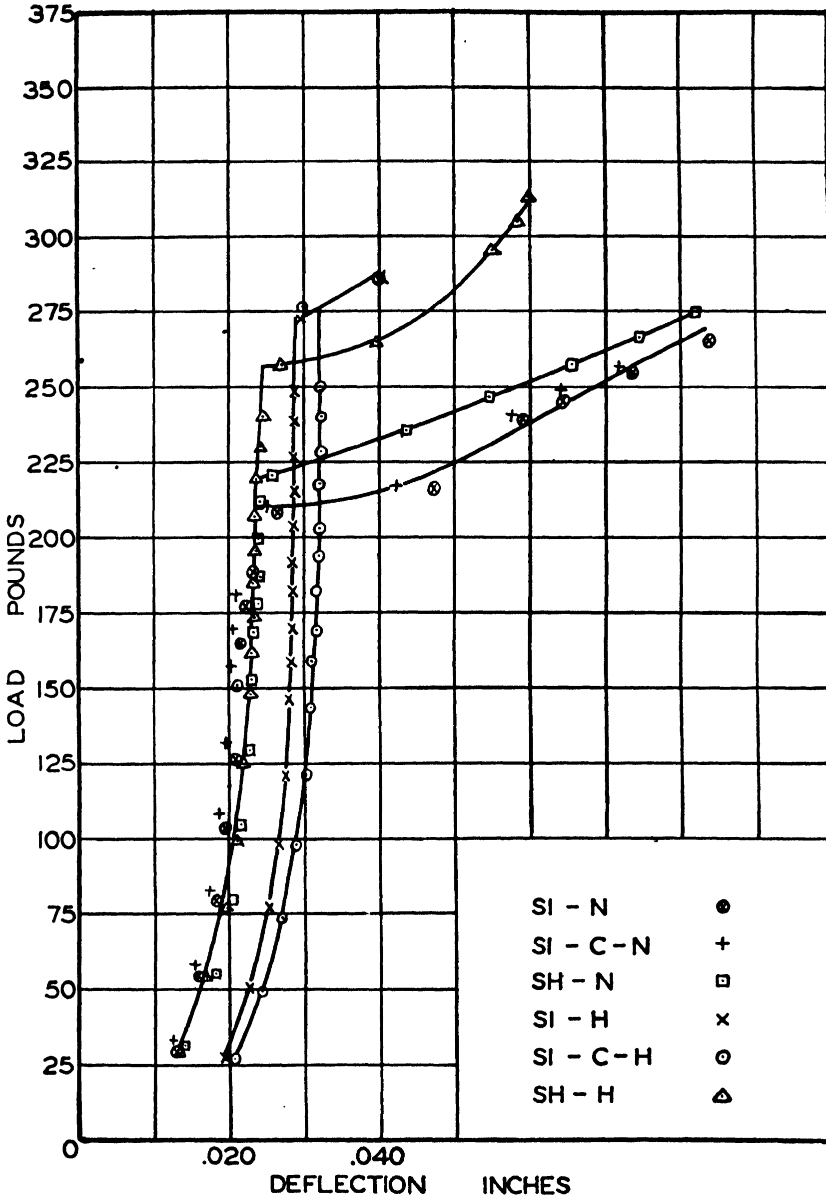

Figure 7. Load-Deflection Curves—Flat Compression Test.

times when the initial resistances of the boards to crushing were overcome and collapse of the boards began. These are the loads at the breaks in the curves in Figure 7. Observation of the board at this point showed that the tips of the corrugations were flattened against the liners, so that in cross section the corrugations appeared as squares or trapezoids. When the corrugations were in this form, the board resisted compression as the load on the board increased to the initial collapse point. The corrugating medium acts as a series of rigid columns and at the initial breaking load these columns of corrugating medium buckle and collapse.

The resistance of board to compression up to the initial breaking point is evidently due to the ability of the column of corrugating medium to resist compression. Such resistance should be greater with shorter columns. The data in Table VIII and Figure 7 indicate this, as the boards with the greater initial crushing load values compressed more before collapsing, thus the tips of the corrugations were flattened to a greater extent and the column of corrugated medium shortened. The extent the corrugating medium flattens against the liner appears to be determined by area at the tips of the corrugations which is covered by adhesive and this area is evidently greater with silicate adhesive.

Study of the data in Table VIII reveals that of the boards made with normal applications of adhesives, the starch pasted board had about a ten per cent greater initial crushing strength than the boards made with silicate adhesives. Both the latter boards gave nearly the same test. When heavy applications of adhesive were used, the silicate boards showed a considerable increase in initial compression strength over the values with normal application, so that silicate boards had about ten per cent greater strength than the starch pasted board.

The ultimate crushing load is the load that causes complete collapse of the board. Between the initial and ultimate load values the board is continually collapsing as shown in Figure 8. Often a complete collapse occurs simultaneously with the initial one, and complete collapse of the board is usually obtained at the initial crushing load if the initial crushing load is maintained steadily for a sufficient period.

For the six boards evaluated, the starch pasted boards had the highest ultimate crushing load values within the two groups, that is, normal and heavy applications of adhesive. It is interesting to note that the two silicate boards made with heavy applications of adhesive, Si–H and Si–C–H, gave initial and ultimate crushing load values which were nearly the same. Usually these boards completely collapsed at the initial crushing load.

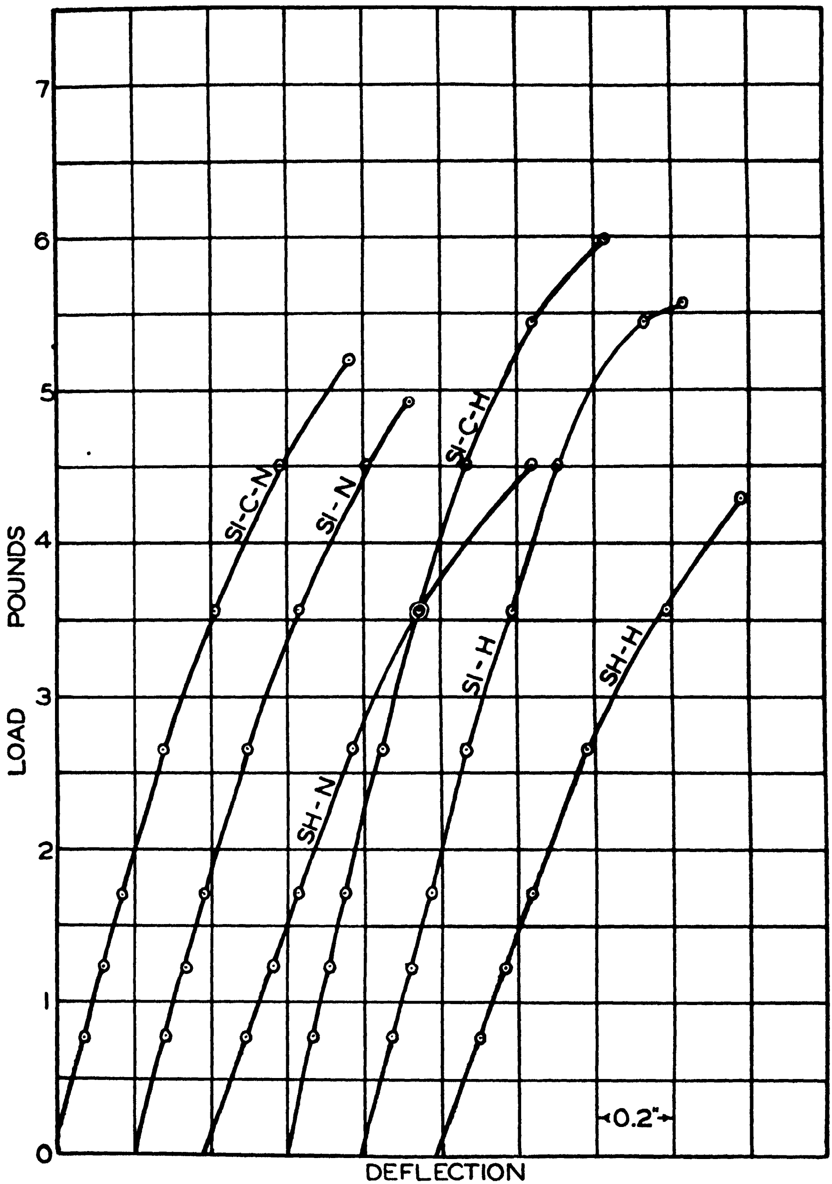

Figure 8. Load-Deflection Curves—Transverse Beam Test, 50% Relative Humidity, Corrugations Parallel to Beam Length, Single Face Up.

The resistance of corrugated fiberboard to compression is evidently dependent in part upon the ability of the corrugating medium to resist compression, and the influence of the adhesive. The adhesive influences the crushing load that may be sustained by the extent to which it covers the tips of the corrugations, and thereby determines the height of the column of corrugating medium that has to withstand the load.

Indications have been obtained from a few tests that the complete impregnation of the corrugating medium by silicate of soda will markedly increase both the column and flat compression test values.

Mullen Strength Tests: The results of the Mullen strength tests are reported in Table IX. The only consistent relationship in this Table is that

TABLE IX
*Mullen Strength Tests**

Board		Single Face Up	Double Face Up
Adhesive	Application		
Silicate	Normal	226.8	219.2
Silicate-Clay	Normal	232.6	210.2
Starch	Normal	243.6	244.7
Silicate	Heavy	234.4	223.4
Silicate-Clay	Heavy	216.4	229.3
Starch	Heavy	247.3	235.2

* Average 10 tests at 50% Relative Humidity.

starch pasted boards have greater Mullen strength values than silicate boards. There were little differences in the Mullen strengths of the boards due to the use of larger amounts of adhesive.

It was noticed during the testing that the type of failure of silicate boards was different from that with starch boards. The silicate boards usually compressed before breaking, while the starch boards compressed and burst simultaneously.

A comparison of the Mullen strengths of boards and the compression strengths of boxes is given in Table I. This comparison is interesting in that the Mullen strength, which is usually accepted as a standard means of evaluating the qualities of fiberboard, does not correlate with box strength nor does it correlate with the values obtained from the structural tests made on fiberboard.

Bond Strength Tests: The results of the bond strength tests are reported in Table X. The values indicate that the bond strength of starch pasted board was greater than the bond strength of silicate boards when normal applications of adhesive were used. The reverse is true with

heavy applications of adhesive, that is, the silicate boards had greater bond strengths than the starch board. Except for one value which is evidently in error, the silicate boards had comparatively the same bond strengths.

The bond strength as measured is of doubtful value. There are many ways of obtaining bond strength, and the results reported may be considered consistent with the type of test used.

TABLE X
*Bond Strength Tests**

Board		Rupture Load, lbs.	
Adhesive	Application	Double Face Bonds	Single Face Bonds
Silicate	Normal	32.0	42.2
Silicate-Clay	Normal	55.0	41.0
Starch	Normal	58.0	46.0
Silicate	Heavy	61.5	50.0
Silicate-Clay	Heavy	63.0	51.2
Starch	Heavy	58.8	47.3

* Average 3 tests at 50% Relative Humidity.

Paperboard Compression Tests: The results of the compression tests on columns of liners from corrugated board are given in Table XI. These were samples of liner from which the corrugating medium had been removed as completely as possible without damaging the adhesive line.

The compression tests on samples of liners on which the adhesive lines were horizontal are essentially the same. This should be true as the liners are only as strong as the strength of the paper between the adhesive lines.

The compression tests of the samples of liners on which the adhesive

TABLE XI
*Compression Tests on Liners**

Board		Corrugations Horizontal		Corrugations Vertical	
Adhesive	Application	50% R. H.	70% R. H.	50% R. H.	70% R. H.
		lb.	lb.	lb.	lb.
Silicate	Normal	91.0	73.2	109	97.2
Silicate-Clay	Normal	88.3	73.2	115	94.7
Starch	Normal	88.3	70.5	100	94.7
Silicate	Heavy	82.0	73.2	119	97.2
Silicate-Clay	Heavy	80.5	73.0	136	106.0
Starch	Heavy	82.0	73.0	107	101.0

* Average of 10 tests at 50% Relative Humidity.

lines were vertical are considerably higher than the preceding tests. Normally they should be considerably less as these tests were made across the grain of the paper. The comparison can be made with the crushing strength tests in Table II. These tests are greater, due to the strength contributed to the paper by the adhesive. Heavier applications of adhesive tended to increase the crushing strength.

THEORETICAL CONSIDERATIONS

Recognition of corrugated paper board and the boxes made from it as structural materials, prompts analysis of the board and structures in the ways commonly used with other materials. Almost all structural materials are elastic bodies in that they return to initial dimensions after moderate distortion and fail when forces are large enough to distort the material permanently. Corrugated fiberboard and its structures have similar elastic properties. The load deflection data from the beam tests as plotted in Figures 8–12 show this elasticity. The first portion of these curves may be considered straight lines and within these limits the board acts as an elastic body. At greater loads the amount of deflection increases in greater proportion, giving curvature to the lines.

Modulus of Elasticity:

The force required to produce a unit of deflection as long as the beam acts as an elastic body is called the modulus of elasticity. It is a measure of the stiffness of a material. The modulus of elasticity of a material is a basic property and appears in formulations on the strength of structures. It is an important property of corrugated board, which must act as a column and a beam when fabricated into a box, as the board which forms a side of a box acts as a column when the box is subjected to a compressing load, and it resists a side thrust on the box by acting as a beam.

The moduli of elasticity of the corrugated fiberboards used in this research were computed from the data obtained in the transverse beam and column compression tests. The formulations used and the methods of computation are presented in the appendix. The formulations require the moment of inertia of the board and a computation of the moment for a cross section perpendicular to the corrugations appears in the Appendix. The moment of inertia of a cross section parallel to the corrugations can not be readily computed. Thus, the moduli were determined from column data obtained with corrugations vertical and from beam data obtained with corrugations parallel to the beam. The beam data obtained at two pounds load were used.

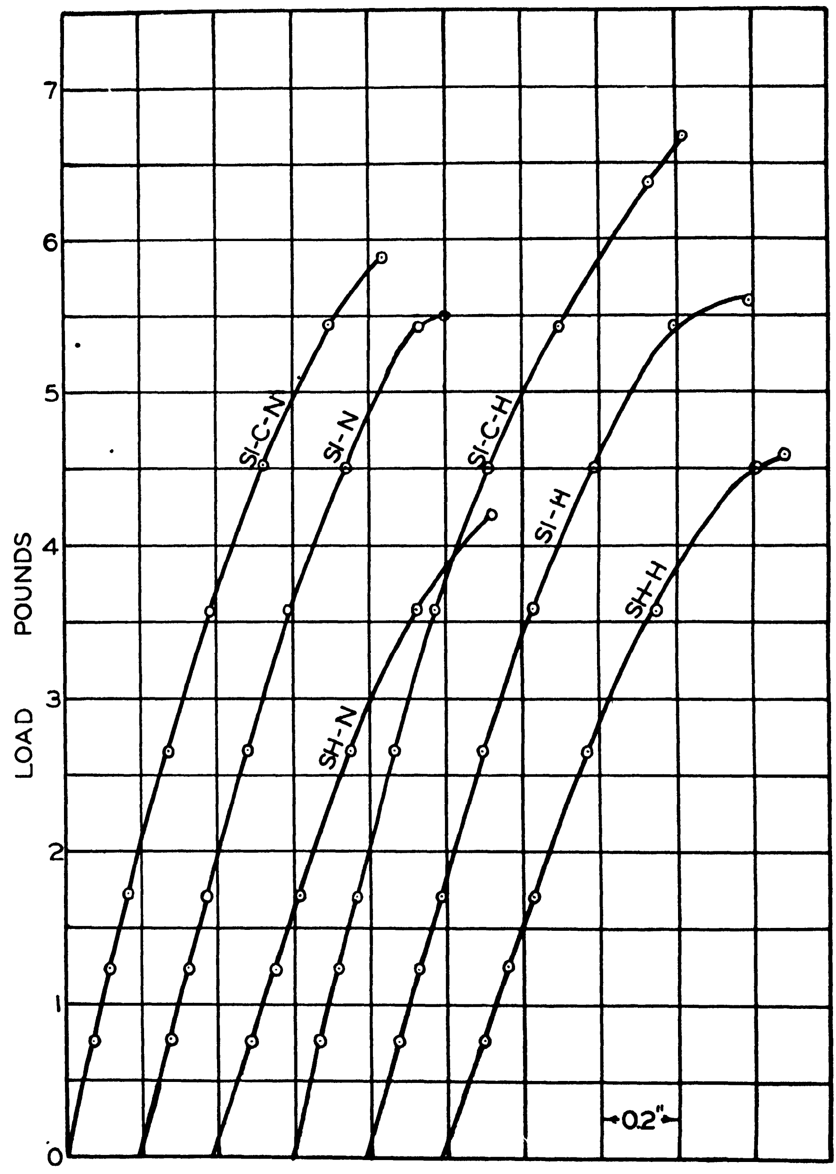

Figure 9. Load-Deflection Curves—Transverse Beam Test, 50% Relative Humidity, Corrugations Parallel to Beam Length, Double Face Up.

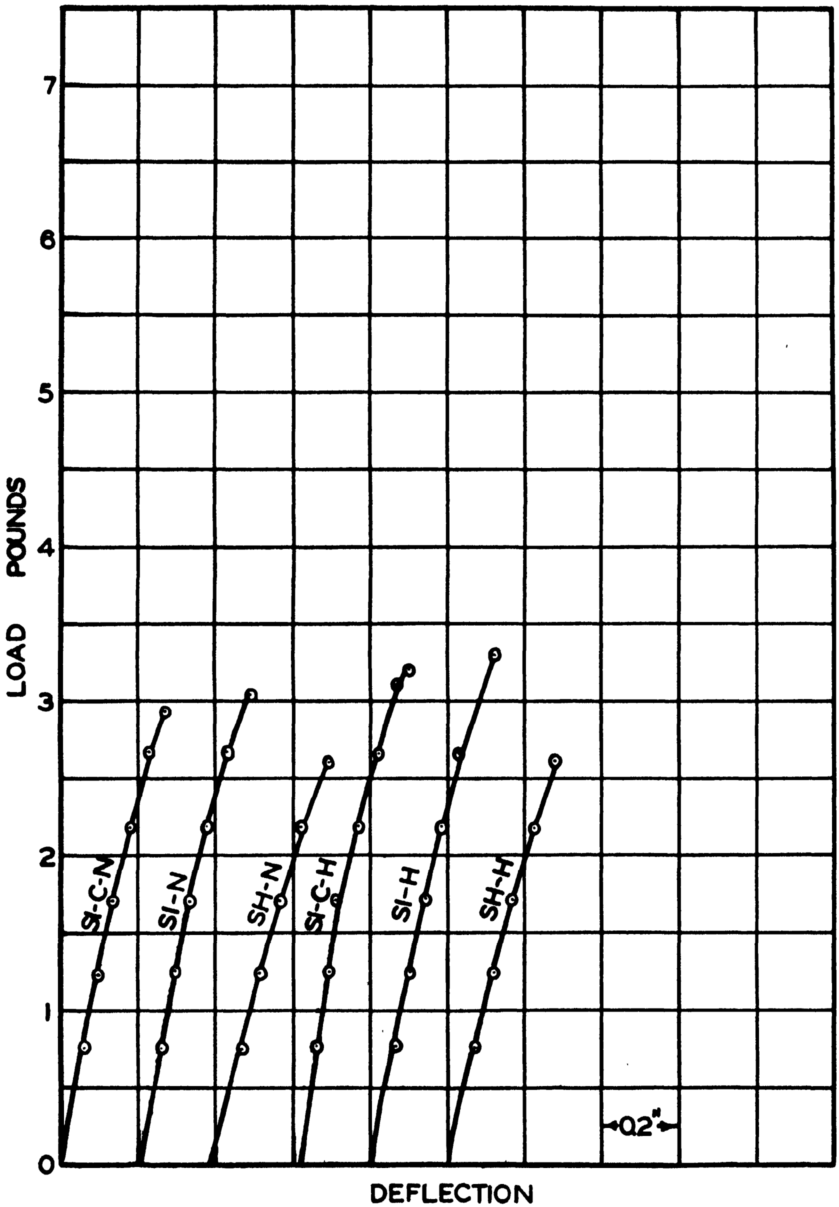

Figure 10. Load-Deflection Curves—Transverse Beam Test, 50% Relative Humidity, Corrugations Perpendicular to Beam Length, Single Face Up.

The computed moduli of elasticity of the boards at 50% relative humidity are given in Table XII.

TABLE XII
Moduli of Elasticity

Board		Column Moduli	Beam Moduli		
			Corrugations Parallel		Ave.
Adhesive	Application		Single Face Up	Double Face Up	
Silicate	Normal	179,700	283,000	298,000	290,500
Silicate-Clay	Normal	196,200	306,000	308,000	307,000
Starch	Normal	160,000	229,000	243,000	236,000
Silicate	Heavy	217,500	306,000	287,000	296,500
Silicate-Clay	Heavy	233,000	343,000	318,000	330,500
Starch	Heavy	169,500	222,000	234,000	228,000

The values of Table XII show that the moduli of elasticity of silicate-clay boards are the larger so that these may be considered the stiffer boards. The starch boards have the lowest moduli values. The use of a heavy application of adhesive appreciably increases the stiffness of boards, particularly those glued with silicate adhesives.

Computation of the Strength of Corrugated Fiberboard Boxes:

The modulus of elasticity of a material is a measure of the rigidity of the material, and is used in computations of the strength of structures made from the material. Thus, it should be possible to predict the strength of a corrugated fiberboard structure, such as box, from the modulus of elasticity of the fiberboard.

Prediction of box strength from moduli data was obtained by considering a box the equivalent of a four-sided, square, hollow column. The formulations and sample computations are presented in the Appendix. There may be some question regarding the formulation selected. However, in all formulations applicable to structures such as boxes, the strength of the box is proportional to the modulus of elasticity and other items in the formulae are constant for similar sizes and shapes of boxes. The formulation chosen was the one of several which most closely described the structural properties of a box.

The strength of the boxes as computed from the moduli of elasticity of the boards and as determined experimentally are given in Table XIII. The values for board Silicate Normal check exactly as the data, for this board and the boxes made from it, were used to obtain the shape factor for the computation.

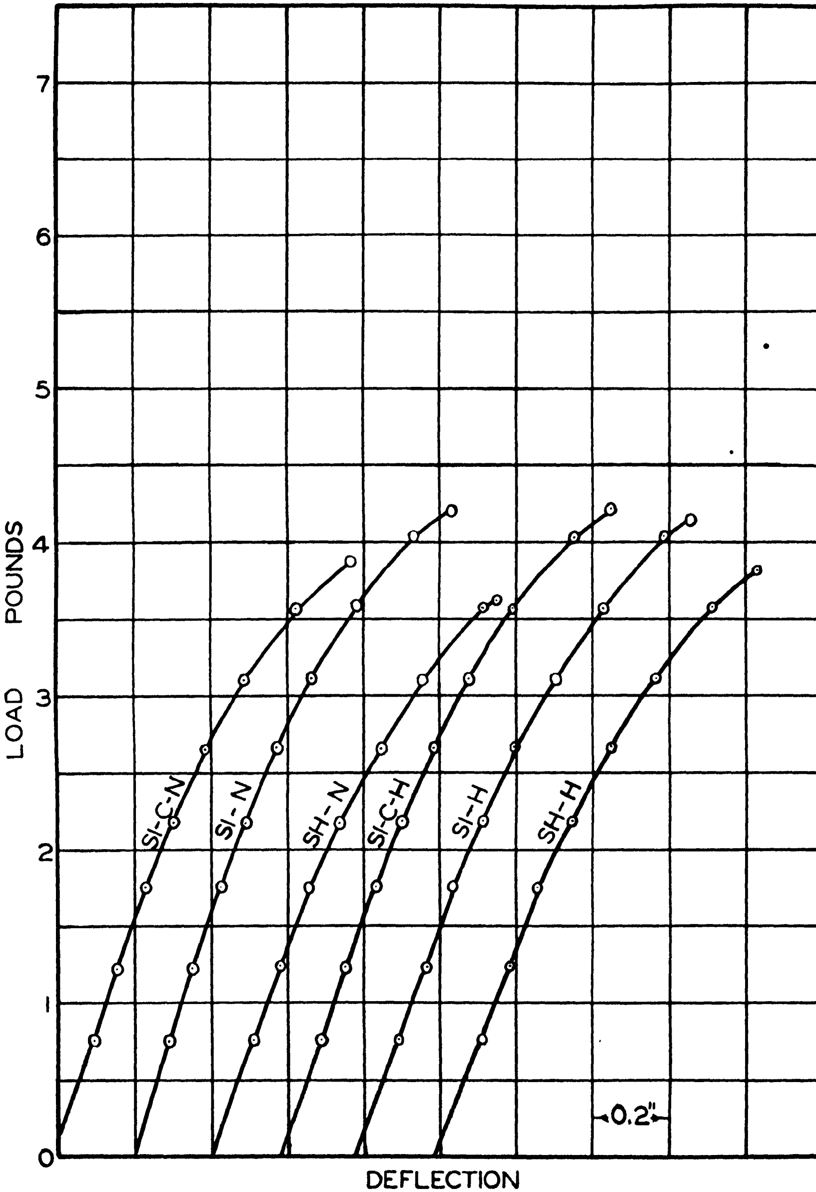

Figure 11. Load-Deflection Curves—Transverse Beam Test, 70% Relative Humidity, Corrugations Parallel to Beam Length, Single Face Up.

The results in Table XIII show a rather close agreement between measured box strengths and box strengths as computed from the column moduli. Thus the column compression test value may be considered as indicative of box strength. The box strengths, as computed from beam moduli, are, in general, less than measured strengths. Better correlation would have been obtained if a board other than Silicate Normal had been chosen as standard, but the general agreement between boards would have been the same. The silicate boards show much greater box strengths than starch boards when computed by the beam moduli.

The results of these correlations between computed and measured box strengths affirm previous statements, that corrugated fiberboard may be

TABLE XIII

Experimental and Computed Compression Strengths of Boxes

Board		Computed Strength in Lbs.		Experimental Strength
Adhesive	Application	Column Modulus	Beam Modulus	
Silicate	Normal	1021	1021	1021
Silicate-Clay	Normal	1115	1063	1082
Starch	Normal	910	817	916
Silicate	Heavy	1235	1030	1229
Silicate-Clay	Heavy	1324	1160	1074
Starch	Heavy	965	790	899

treated as a structural material, and as such, the strengths of boxes made from it are proportional to the modulus of elasticity of the board.

In a search for a structure that could be evaluated to test the relationship between modulus of elasticity and strength of a structure, a square column 10×10×10 inches, without ends, was used. Also, 10×10×10 inch boxes were made in the laboratory. When these were tested, the following results were obtained for boxes and columns made for board Silicate-Clay Normal.

Quinn box strength— 1082 lbs.
University box strength—1092 lbs.
Hollow column strength—1574 lbs.

It is surprising and significant that the hollow square column gives about 50% greater test than fully fabricated boxes. A satisfactory explanation is not available at present. Attempts should be made to explain this phenomenon so that the ultimate possible strength may be realized in the box structure.

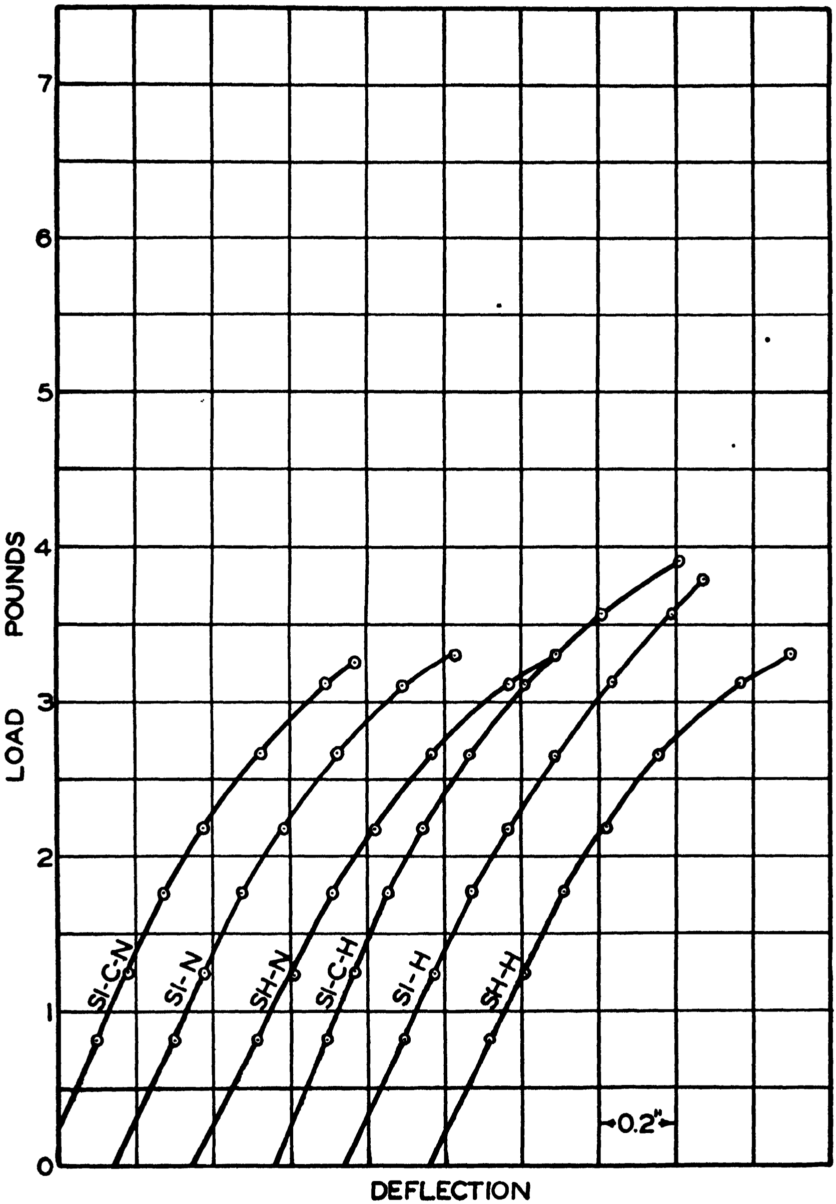

Figure 12. Load-Deflection Curves—Transverse Beam Test, 85% Relative Humidity, Corrugations Parallel to Beam Length, Single Face Up.

CONCLUSION

This report presents the data obtained and the conclusions drawn on a study of the properties of corrugated fiberboard and boxes. The effect of the adhesive on strength properties has been evaluated and the data obtained analyzed in a fundamental manner.

It is hoped that research will reveal further clarifications of the important relationships between the properties of fiberboard, adhesive, and strength of fiberboard structures.

APPENDIX

Computation of Moment of Inertia:

In the computation of the moment of inertia, I, an assumption must be made as to the geometric shape of the corrugating medium. This was taken to follow quite closely the form of an ellipse. Several sets of measurements were made on the finished board and the dimensions shown in the accompanying sketch obtained, Figure 13.

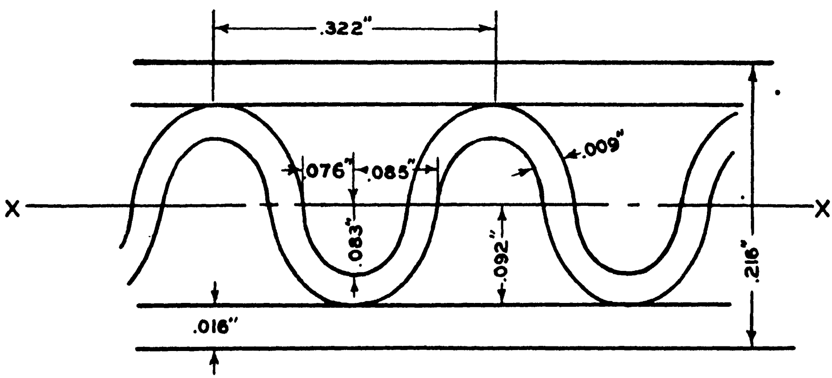

Figure 13. Dimensions of Cross-Section of Corrugated Board.

The method of computation is to sum the moments of inertia of both lines and the corrugating medium computed with respect to the centroidal axis XX.

Moment of Inertia of Corrugating Medium, I_c; the moment of inertia of the ellipse is given as*

$$I_c = \frac{\pi}{4}\,(a^3 \times b - a_2^3 \times b_2)$$

in which a and b are major and minor axes of the ellipses respectively. For the corrugating medium $a = 0.092$, $b = 0.085$, $a_2 = 0.083$ and $b_2 = 0.076$, and a full ellipse occurs every 0.322 inches.

Thus

$$I_c = \frac{\pi}{4}\,(0.092^3 \times 0.085 - 0\ 083^3 \times 0.076)$$

$$I_c = 0.0000227 \text{ in.}^4$$

* Elements of Strength of Materials—Timoshenko & MacCullough, p. 339.

This value is for one cycle of 0.322 inches, so for a distance of one inch

$$I_c = \frac{0.0000227}{0.322} = 0.0000705 \text{ in.}^4$$

Moment of Inertia of liners, I_L; the moment of inertia of a liner in respect to the centroidal axis of the board is

$$I_L = \frac{bh^3}{12} + ad^2$$

where

b = width of 1 in.
h = thickness of the liner
a = area of liner = bh
d = distance from center of liner to centroidal axis, XX.

The first term is the moment of inertia of the liner in respect to its own centroidal axis and the term ad^2 changes the moment to the moment of inertia in respect to the centroidal axis, XX, of the corrugated board.

$$I_L = \frac{1 \times 0.016^3}{12} + 0.016 \times 0.100$$
$$= 0.00016 \text{ in.}^4$$

Total moment of inertia; the total moment of inertia of the corrugated board per inch of cross section is obtained by summation to the moments of the corrugating medium and liners.

$$I = (2I_L) + I_c$$
$$= 0.00039 \text{ in.}^4\text{/inch length.}$$

CALCULATION OF MODULUS OF ELASTICITY FROM COLUMN DATA

In computing the modulus of elasticity from the data obtained by the buckling of the 4″×4″ columns, the following equation* applies:

$$P_{cr} = \frac{\pi^2 EI}{l^2} \text{ in which}$$

P_{cr} = Load at breaking point, lbs.
l = Length of column, in.
E = Modulus of elasticity, #/in.²

* Elements of Strength of Materials, Timoshenko-MacCullough, pg. 264.

I = Moment of inertia, in.^{4}
π = Constant, 3.1416.

This equation applies to the fundamental case of buckling in which the ends are not restrained.

The value of I has been computed and in the case of the 4″×4″ specimen used in the column test has a value of 0.00156 in.^{4}.

$$l = 4 \text{ in.}$$

Solving for E and substituting in the values necessary

$$E = \frac{P_{cr} l^2}{\pi^2 I}$$

$$E = \frac{P_{cr} 4^2}{\pi^2 0.00156} = 1040\ P_{cr}.$$

CALCULATION OF MODULUS OF ELASTICITY FROM BEAM DATA

The equation for the bending of a beam supported at both ends and the load concentrated at the center, is given as

$$D = \frac{P_e l^3}{48\ EI} \text{ in which}$$

D = deflection at center, in.
P_e = load at center, lbs./in. width
l = distance between supports, in.
E = modulus of elasticity, #/in.^{2}
I = moment of inertia, in.^{4}.

Solving the above equation for E, the modulus of elasticity,

$$E = \frac{P_e l^3}{48\ DI}.$$

In this equation the data from 3×12 inch beam tests were substituted.

I = 0.00039 in.^{4}/in.
l = 12 in.
D = experimentally determined deflection
P_e = the experimentally determined load, P, divided by the width of the beam = $P/3$.

Using these values the basic equation simplifies to

$$E = \frac{30{,}750\ P}{D}\ .$$

The experimentally determined values of P and D from the beam test were substituted to compute the modulus of elasticity.

COMPUTATION OF THE STRENGTH OF FOUR-SIDED, SQUARE, HOLLOW COLUMNS AND OF BOXES

Computation of the strength of corrugated fiberboard structures was obtained by use of the following formulae for the strength of four-sided, square, hollow columns made from thin plates. Other formulations may have been used, but all formulations are similar in that strength is proportional to the modulus of elasticity, and are different only in the variables concerned with shape factors.

$$^{*}N_a = \frac{k\pi^2 E h^3}{12(l-v^2)b^2}$$

N_a = critical stress per inch perimeter
k = shape factor (ratio of dimensions of plate)
E = modulus of elasticity
h = equivalent thickness of board
b = width of board

$$v = \text{Poisson's Ratio}\left(\frac{\text{unit lateral contraction}}{\text{unit axial elongation}}\right).$$

As the value of Poisson's ratio for corrugated board is rather indeterminable and should be practically constant, the term $k/l-v^2$ may be considered as a constant K.

Then,

$$N_a = \frac{K\pi^2 E h^3}{12b^2}\ .$$

The equivalent thickness of the board, h, was determined as the thickness of a rectangular section which has the same moment of inertia as the section of corrugated board.

For a rectangular section, $I = (h^3/12)$, thus

$$h^3 = 0.00039 \times 12 = 0.00468.$$

* Timoshenko, S., Theory of Elastic Stability, p. 330, McGraw-Hill Book Co., 1936.

The value of b, the width of the side of a column is determinable in the case of square columns. For the boxes used in this work which were $13\frac{3}{4} \times 10\text{-}^{5}/_{16} \times 9\frac{5}{8}$, b can be considered either as $13\frac{3}{4}$ or $10\text{-}^{5}/_{16}$ inches. In the formulation of N_a, the critical stress per inch of perimeter decreases as the dimensions of the sides of the boxes increase, so that the $13\frac{3}{4}$ inch side is weaker per inch than the $10\text{-}^{5}/_{16}$ inch side. Considering this, the dimension of b was taken as $13\frac{3}{4}$ inches.

The total strength of the box equals N_2 times the perimeter, or:

$$P = N_a \times 2(13.75 + 10.31)$$

$$P = 48.12 \left[\frac{K \times \pi^2 \times E \times 1.00468}{12 \times 13.75^2} \right]$$

$$P = 0.00098\ EK.$$

In this formulation, K may be considered a "shape factor" which is dependent upon the dimensions of the box, and is constant for boxes with similar dimensions. K can be evaluated by using experimental data, and this is done by considering the boxes made from Silicate-Normal board as standard. These boxes gave a test of 1021 pounds in the compression test. By substitution of $P=1021$ and the moduli of elasticity of Silicate-Normal board from Table XII, K may be evaluated.

For column test moduli:

$$1021 = 0.00098 \times 179.700 \times K$$

$$K = 5.80.$$

For beam test moduli:

$$1021 = 0.00098 \times 290.500 \times K$$

$$K = 3.53.$$

The strength of the boxes made from the other lots of corrugated board were then computed from the moduli of elasticity given in Table XII by the following formulation.

For column moduli:

$$P = 0.00098 \times 5.8 \times E.$$

For beam moduli:

$$P = 0.00098 \times 3.53 \times E.$$

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